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13. ABSTRACT (Maximum 200 words) <p>Described is the synthesis of a ladder polymer with a poly(p-phenylene) (PPP) backbone. The main PPP backbone was synthesized via palladium-catalyzed coupling of an arylbis(boronic ester) with an aryl dibromide. Imine bridges, formed by exposure of the polymer to trifluoroacetic acid, are used to force the consecutive units into planarity. The bridging units are sp^2 hybridized thus allowing for greater π-electron flow between the consecutive phenyl units by lowering the band gap between the hydroquinoidal and the quinoidal forms of the phenylene backbone. When the bridges are n-dodecyl substituted, the fully planar structures (with $M_n < 5000$) are soluble in hot chlorobenzene from which flexible free standing films can be cast. The n-butyl substituted polymers and the higher molecular weight n-dodecyl substituted polymers are soluble in CH_2Cl_2/trifluoroacetic acid mixtures. The optical spectra of the planar systems are compared to that of the parent nonplanarized polymers, some analogous planar oligomers, and oligo(p-phenylenes).</p> <p style="text-align: right;">DTIC QUALITY INSPECTED 8</p>			
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Synthesis of Planar Poly(*p*-phenylene) Derivatives for Maximization of Extended π -Conjugation

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Synthesis of Planar Poly(*p*-phenylene) Derivatives for Maximization of Extended π -Conjugation

James M. Tour* and Jaydeep J. S. Lamba

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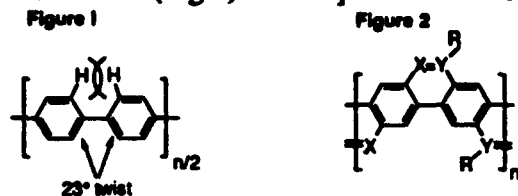
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Abstract

Described is the synthesis of ladder polymers with a poly(*p*-phenylene) (PPP) backbone. The main PPP backbone was synthesized via palladium-catalyzed coupling of an arylbis(boronic ester) with an aryldibromide. Imine bridges, formed by exposure of the polymer to trifluoroacetic acid or HCl, are used to force the consecutive units into planarity. The bridging units are sp^2 hybridized thus allowing for greater π -electron flow between the consecutive phenyl units by lowering the band gap between the hydroquinoidal and the quinoidal forms of the phenylene backbone. Upon planarization, bathochromic shifts of 210-240 nm occur for the *n*-dodecyl substituted polymer. The optical spectra of the planar systems are compared to that of the parent nonplanarized polymers, oligo(*p*-phenylenes), PPP, and other near-planar PPP derivatives. When the bridges are *n*-dodecyl substituted, the fully planar structures can be made into flexible free standing films.

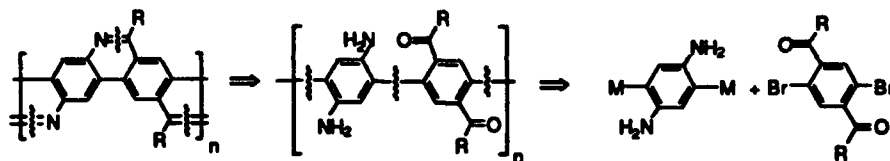
Poly(*p*-phenylene) (PPP),¹ a highly insoluble polymer that has been studied extensively for its possible electronic and photonic applications, has a 23° twist^{1c,2} between the consecutive aryl units due to ortho hydrogen interactions (Fig 1). Attempts to enhance the solubility by substitution



of the rings forces the consecutive aryl units even further out of plane resulting in a plummet of the extended conjugation (easily observed by the optical spectra).^{1i-k} Here we describe a synthetic route to ladder³ PPP derivatives with bridges that (1) form in high yields upon protonic activation once the PPP backbone is intact, (2) can be substituted so that the newly formed polymer is soluble, unlike many other aromatic ladder polymers, (3) contain a double-bonded unit to keep the consecutive aryl units planar while maximizing extended π -conjugation through the PPP backbone thereby increasing the band width (lowering the band gap) between the hydroquinoidal and quinoidal forms (Fig 2),^{1c} and (4) can be film cast in the uncyclized form followed by protonic activation to obtain films of the planarized system.

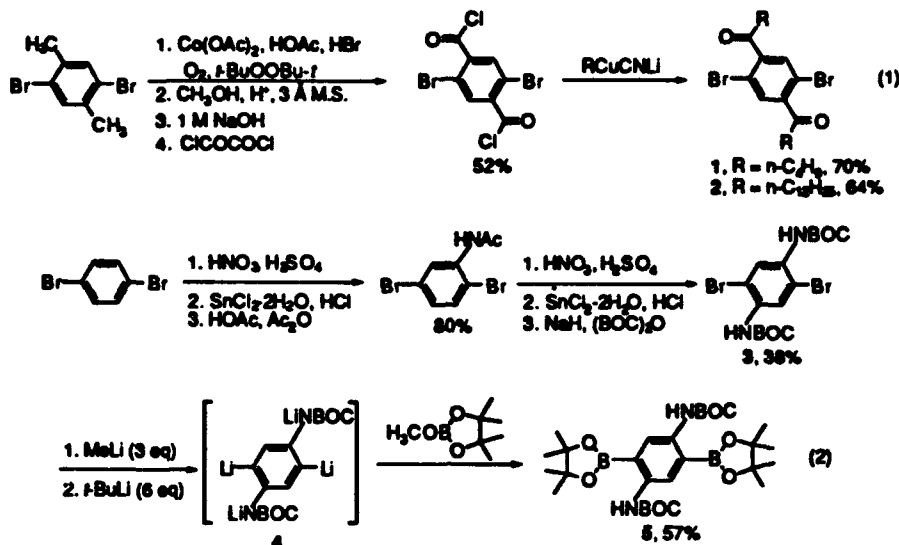
Our retrosynthetic approach involved two key steps (Scheme I, M = metal). First,

Scheme I



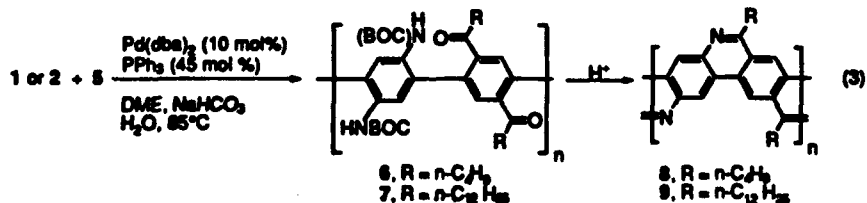
imine cleavage to the ketoamine functionalized PPP, and second, bond cleavage to the two arene systems shown. Since Pd(0)-catalyzed oxidative addition reactions are facilitated with electron deficient ring systems,⁴ we chose to keep the halides on the ketoaromatic portion.

After several nearly quantitative model reactions, we synthesized the two key monomers needed for the desired AB-type step growth polymerization (eqs 1 and 2).⁵ It is remarkable that while 3 was nearly insoluble in ether, it could be tetralithiated in ether to form a soluble intermediate 4 in almost quantitative yield (checked by addition of TMSCl and isolation of the



aryl(bis(silane) after aqueous work-up). Treatment of 4 with methyl pinacol borate afforded the monomer 5 which could be purified by passage through a flash chromatography column containing a mixture of activated charcoal and Celite as the stationary phase (silica gel or neutral alumina caused rapid decomposition of the intermediate) and CH_2Cl_2 as the eluant followed by recrystallized to form pure 5.⁶

Reaction of 1 or 2 with 5, in the presence of a $\text{Pd}(0)$ catalyst, yielded the soluble polymers 6 and 7, respectively, from which size exclusion chromatography (SEC) could be used to determine the hydrodynamic volumes relative to polystyrene (6: 63% yield after fractional precipitation, $M_n = 9,850$ with $M_w/M_n = 1.85$; 7: 97% yield after fractional precipitation, $M_n = 28,400$ with $M_w/M_n = 3.70$). Upon exposure of 6 or 7 to trifluoroacetic acid (TFA), quantitative loss of the BOC protecting group and cyclization afforded 8 (90% yield) and 9 (97% yield), respectively (eq 3).^{7,8} All stretches for the ketone, carbamate, and amine in 6 and 7 were absent in the FTIR spectrum of 8 and 9.

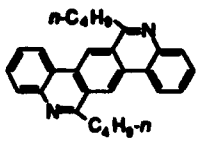
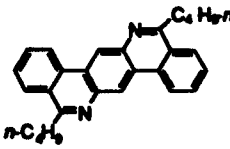
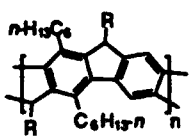


Samples of **8** and **9** can be solubilized with $\text{CH}_2\text{Cl}_2/\text{TFA}$ (3:2) mixtures. Additionally, **7** can form THF solution-cast films then be cleanly cyclized by suspension of the film in anhydrous HCl/EtOAc followed by proton removal with $\text{Et}_3\text{N}/\text{NaOH}$ to afford **9** as a flexible free-standing film. Again, this film was devoid of ketone, carbamate, and amine absorptions in the FTIR spectrum. Therefore, the dodecyl groups are apparently exerting a plasticizing effect so that even this planar rigid rod polymer can possess good film forming properties.

Powder X-ray diffraction (XRD) of annealed **8** showed a broad pattern at 14 and 41 Å while **9** showed a similar pattern at 27 and 45 Å. Differential scanning calorimetry (DSC) (50–350°C, 20°C/min, N_2) thermograms of **8** and **9** were featureless on both the first and second heating cycles. Thermogravimetric analysis (TGA) (50–900°C, 20°C/min, N_2) of **9** showed an onset of major weight loss at 400°C, 10% weight loss at 434°C, and 50% weight loss at 550°C. The TGA thermogram of **8** was similar. Most exciting is the optical absorption data showing enormous bathochromic shifts in the polymers upon cyclization (conversion of **6** to **8** and **7** to **9**); an observation consistent with the proposed ladder formation (Table I). Also interesting are the large hypsochromic shift in the spectrum of protonated **9** (solution) relative to **9** in the neutral form (solid), suggesting that cationic nitrogen atoms retard the extended conjugation. The absorptions of these planar polymers are far more bathochromically-shifted than those of the planar trimers,⁹ oligo(*p*-phenylenes), and PPP,¹⁰ while the λ_{max} values are in the range of other near-planar PPP derivatives that have been synthesized.¹²

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Table I. Optical Absorption Data

Compound	λ in solution (nm) ^a	λ of solid (nm) ^a
6	CH ₂ Cl ₂ : <u>250</u> , 306 (sh)	<u>248</u> , 308 ^b
7	CH ₂ Cl ₂ : <u>250</u> , 388	<u>250</u> , 398 ^b
8	CH ₂ Cl ₂ /TFA: 374, <u>396</u> , 426 (sh), 514, 520 (ed) ^c	---
9	CH ₂ Cl ₂ /TFA: 376, <u>400</u> , 428, 478, 516, 530 (ed) ^c	<u>463-490</u> ^d
	CH ₂ Cl ₂ : <u>300</u> (ref 9)	---
	CH ₂ Cl ₂ : <u>294</u> (ref 9)	---
<i>p</i> -sexiphenylene	CHCl ₃ : <u>318</u> (ref 10)	---
PPP (calcd infinite <i>M_n</i>)	<u>344</u> (ref 10)	---
	CH ₂ Cl ₂ : <u>348-443</u> (ref 12)	---

^a λ_{\max} is underlined, (sh) is shoulder, (ed) is tailing edge at ~10% of λ_{\max} intensity.

^bAlso a strong carbonyl absorption at 196 nm. ^cSpectrum recorded on the acid solublized, therefore, multiprotonated system. ^dThese λ_{\max} values were recorded on a series of four different polymer samples of 9 in order to insure their reproducibility.¹¹

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(2) We can also accurately calculated the twist angle on a *p*-phenylene decamer to be 22.3° using MMX with extended π -Hückel parameters. For a discussion of twist angle versus degree of extended conjugation, see: (a) Brédas, J. L. in ref 1c. (b) Ferraris, J. P.; Andrus, R. G.; Hrcir, D. C. *J. Chem. Soc., Chem. Commun.* **1989**, 1318. (c) Gorman, C. B.; Ginsburg, E. J.; Moore, J. S.; Grubbs, R. H. *Polym. Prepr. (Am. Chem. Soc., Div. Polym. Chem.)* **1991**, *32*(3), 714. (d) Orchard, B. J.; Freidenreich, B.; Tripathy, S. K. *Polymer* **1986**, *27*, 1533.

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(5) (a) The *tert*-butylperoxide modified Co-based oxidation was far superior to several permanganate oxidations attempted. See: Hay, A. S.; Blanchard, H. S. *Canad. J. Chem.* 1965, 43, 1306. The dicarboxylic acid was then converted to the diester to facilitate purification. (b) Doornbos, T.; Strating, J. *Org. Prep. Proced.* 1969, 1, 287.

(6) The arylbis(boronic acid) analog of 5 could not be adequately purified for the step growth polymerization.

(7) The twist in 8 and 9 is $<1^\circ$ between the consecutive phenyl rings calculated by MMX with extended π -Hückel parameters.

(8) Highest molecular weight samples of 6 and 7 were obtained when the Pd-catalyzed coupling was done for ~24 h using an equimolar mixture of 1:5 or 2:5, respectively, followed by the addition of a 5-10 mol % excess of 5 with continued heating for 1-2 d. We thank a reviewer for suggesting this monomer addition sequence. 6: Anal. calc'd for $(C_{32}H_{42}N_2O_6)_n$: C, 69.79; H, 7.69; N, 5.07. Found: C, 70.55; H, 7.25; Br, <0.5 ; N, 5.13. 7: Anal. calc'd for $(C_{48}H_{74}N_2O_6)_n$: C, 74.38; H, 9.62; N, 3.61. Found: C, 74.99; H, 9.40; Br, <0.5 ; N, 3.55. 8: Anal. calc'd for $(C_{22}H_{22}N_2)_n$: C, 84.04; H, 7.05; N, 8.91. Found: C, 79.13; H, 6.77; Br, <0.5 ; N, 8.56. 9: Anal. calc'd for $(C_{38}H_{54}N_2)_n$: C, 84.70; H, 10.10; N, 5.20. Found: C, 81.45; H, 9.64; Br, <0.5 ; N, 5.22.

(9) The planar trimers were prepared during our model studies for the polymerizations described here using Pd-catalyzed couplings.

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(11) Drs. R. Gaudiana and P. Mehta of Polaroid Corporation kindly provided the solid-state UV-vis data.

(12) The near-planar benzenoid ladder polymers were prepared by Pd-catalyzed couplings. See: Scherf, U.; Müllen, K. *Makromol. Chem., Rapid Commun.* 1991, 12, 489. Scherf, U.; Müllen, K. *Synthesis* 1992, 23. Scherf, U.; Müllen, K. *Macromolecules* 1992, 25, 3546.